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NONTHERMAL GAMMA-RAY EMISSION FROM BLAZARS

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ABSTRACT

The leading models proposed to explain the luminous hard γ-ray emission from blazars observed by EGRET and COMPTEL are reviewed in light of the current observational information. The most recent multiwaveband data indicate that high γ-ray states are associated with strong synchrotron flares at lower frequencies. Models involving inverse Compton scattering in a relativistic jet appear to hold the most promise of explaining the γ-ray emission if one considers the general problem of explaining blazar emission across all wavebands. However, the source of the seed photons is controversial, with the synchrotron photons, ultraviolet photons from the putative accretion disk, and photons from diffuse scattering or emission-line regions all competing with each other. Future intensive multiwaveband monitoring of bright γ-ray blazars should lead us to the correct emission model, and may also uncover important clues regarding the nature of the particle acceleration and jet formation in quasars and similar objects.

INTRODUCTION

The highly luminous γ-ray emission observed by EGRET and COMPTEL from bright radio quasars and BL Lacertae objects (collectively referred to as "blazars") is clearly nonthermal in nature. Since these objects also produce strong nonthermal emission at radio to X-ray frequencies, a natural question is whether there is a direct relationship between γ and radio–X-ray radiation in these objects. If there is a close connection, the γ rays could provide an excellent probe for exploring the nature of blazars.

Much has already been learned about the structure and kinematics of the synchrotron emitting regions in blazars. Very Long Baseline Interferometry (VLBI) images at radio frequencies have revealed that the emission is mainly confined to narrow jets, with bright knots of emission that move away from a stationary "core" at apparent velocities exceeding c, the speed of light (see reviews in Zensus and Pearson 1987). The explanation most consistent with the massive data on this phenomenon is that the plasma in the jet is flowing from the nucleus at a highly relativistic speed (Lorentz factor Γ) at an angle $\theta \sim \Gamma^{-1}$ to the line of sight; this creates the illusion of superluminal motion. A major consequence of this is that the emission is beamed toward the observer such that the apparent luminosity is a factor of $\sim \Gamma^{3\pm1}$ higher than in the rest frame of the plasma.

It is also clear that the γ radiation is beamed. Photons with energies exceeding about 100 MeV cannot penetrate an ambient X-ray photon field of the high densities implied by X-ray variability studies without being lost to pair production. Mattox *et al.* (1993) provide a handy formula in terms of observed parameters, and demonstrate that the Doppler factor ($\delta \equiv [\Gamma(1-\beta\cos\theta)]^{-1}$, where βc is the bulk velocity) must be at least 7.6 in the quasar 1633+382 for the observed hard γ rays to escape.

In this paper, we review the basic models for hard γ-ray emission from blazars. We then discuss the current observational data and compare the results with predictions made by the theoretical models. We end by proposing observational tests of the models that can be carried out in the near future.

REVIEW OF MODELS

Since γ rays are electromagnetic waves, they must in general be produced by charged particles, which in turn must have total energies exceeding the energies of the γ rays they generate. The largest cross-section for creating a high-energy γ ray is that of inverse Compton scattering, which is equal to the Thomson cross-section if the energy of the initial photon $h\nu_i \ll \frac{m_e c^2}{\gamma}$, where γ is the Lorentz factor of the kinetic motion of the electron (as opposed to the bulk motion of the plasma containing the electron). In this limit, the photon is scattered up to energy $h\nu_f \sim \gamma^2 h\nu_i$. One can combine these two equations to find that the Thomson cross-section is valid as long as $h\nu_f \ll \gamma m_e c^2$, which is similar (but not quite identical) to the original condition that the electron energy must exceed the final photon energy. Above this limit, the smaller Klein-Nishina cross-section must be used. *The most efficient way that nature has to produce γ rays of energy ~ 1 GeV is therefore to scatter sub-keV "seed" photons by electrons with energies exceeding 1 GeV.* By "most efficient" we mean that the cross-section is highest.

The physical conditions under which inverse Compton scattering is important correspond to highly relativistic electrons immersed in a high-density soft (radio to X-ray) photon field: the energy expended per electron is proportional to the Thomson cross-section times the energy density of photons with frequencies below the Klein-Nishina limit. *Such high photon densities are known to exist in the nonthermal jets of blazars.* In fact, one of the classical problems of radio astronomy has been the high brightness temperatures (with photon energy density being roughly proportional to T_b^5) inferred by converting timescales of variability into maximum size scales, $R \lesssim ct_{var}$ and redshifts into distances. (In some cases, the high values of T_b are measured directly with VLBI; e.g., Marscher and Broderick 1981). The polarization properties and other data mandate that the radio to infrared emission arises from incoherent synchrotron radiation. The inverse Compton scattered emission from such regions emerges at X-ray and γ-ray energies, and is usually referred to as synchrotron self-Compton (SSC) emission (Jones, O'Dell, and Stein 1974). Unless relativistic bulk motion or some other anisotropy of the radiation field is invoked, the SSC X-ray and γ-ray fluxes predicted far exceed those observed for a number of objects (Burbidge, Jones, and O'Dell 1974).

The SSC process must therefore be a leading candidate for the γ-ray production mechanism in blazars. However, one weakness is its tendency to produce curved rather than strictly power-law γ-ray spectra. A related problem cited by some authors is that theoretical SSC spectra do not reproduce the sharp low-energy breaks in the γ-ray region supposedly seen in combined EGRET and COMPTEL data. The sharpness of the breaks appear much more drastic in $E_\gamma^2 F(E_\gamma)$ plots than in $F(E_\gamma)$ spectra — probably because of inappropriate propagation of errors, which must include the uncertainty in the photon energies within a given bin. Nevertheless, as Collmar *et al.* (these proceedings) and Sikora and Begelmen (these proceedings) point out, breaks as high as 1.0 between the X-ray and hard γ-ray regions are demanded by the data and are not readily produced by current SSC models. However, SSC calculations using more realistic geometries (jets and shocks) are in progress (see, e.g. the early results presented by Maraschi, Ghisellini, and Celotti 1992) and are expected to produce spectra different from the case of a uniform sphere. Another criticism, that the Klein-Nishina limit does not permit the TeV γ rays observed from Mkn 421 (Punch *et al.* 1992) to be SSC photons, has been shown to be invalid by Bloom and Marscher (1993) and Zdziarski and Krolik (1993).

The seed photons in the inverse Compton scattering need not originate from the nonthermal jet containing the relativistic electrons. Dermer, Schlickeiser, and Mastichiadis (1992; see also the more detailed calculations in Dermer and Schlickeiser 1993) and Coppi, Kartje, and Königl (1993) have proposed that the electrons in the jet scatter ultraviolet photons from the accretion disk imagined to exist in the innermost regions of an active galaxy according to the standard paradigm. This process is only efficient deep in the jet, at distances from the putative central black hole of order 10^{16} cm, below which the opacity to pair production is too high and above which the photons strike the flowing plasma too close to tail-on for the process to be efficient. Sikora, Begelman, and Rees (1993, 1994) have suggested that the seed photons might come from a nonrelativistic scattering or broad emission line region (i.e., reprocessed accretion disk radiation).

The main advantage of these external inverse Compton scattering (EICS) models is that, if the seed photons strike the relativistic jet from the front or side (actually, from any direction other than nearly tail-on), the photon energies and density are Doppler boosted in the rest frame of the scattering plasma, thereby enhancing the efficiency of the process. In addition, the spectra tend to show less curvature and sharper breaks than the SSC spectra if the seed photon spectrum is strongly peaked, as for thermal radiation. The main problem with EICS models is that the blazars detected by EGRET include both quasars, with strong emission lines and "big blue bumps" considered by many to be thermal radiation from an accretion disk, and BL Lac objects, in which the emission lines are faint or absent and the big blue bump is undetected. Why should objects with such different seed photon luminosities all produce detectable γ rays?

Hadronic collisions can also lead to γ-ray emission through the decay of unstable particles such as pions (e.g., Mastichiadis and Protheroe 1990; Mannheim 1993). However, the cross-section for such processes is more than an order of magnitude lower than the Thomson cross-section, so unless the relativistic proton to electron ratio in jets $\gg 1$, the process is likely to be efficient only close to the central engine where densities are high and from which the hard γ rays would have difficulty escaping without being destroyed by pair production. The same is true for annihilations of relativistic positrons produced either electromagetically (e.g., Lovelace 1976) or through particle collisions and cascades.

Carl Fichtel has been asking the relevant question of how the particles that produce the γ rays get accelerated to GeV or even TeV energies in the first place. In the case of cosmic rays in the Milky Way, the standard model calls for acceleration of both protons and electrons in the shock waves of supernovae. In blazars, shocks have been invoked to explain the superluminal knots in jets (Blandford and Königl 1979; Marscher and Gear 1985; Hughes, Aller, and Aller 1985). In addition, Protheroe and Kazanas (1983) and Mészáros and Ostriker (1983) have proposed that accretion shocks could power the nonthermal jets through particle acceleration. Work on diffusive particle acceleration via the first-order Fermi mechanism at relativistic shock waves indicates that such shocks can indeed accelerate particles, at least theoretically (e.g., Kirk and Schneider 1987; Ostrowski 1993). This is appealing, since shocks can also explain nonthermal flares in blazars (Marscher, Gear, and Travis 1992), which are associated with times of bright γ-ray emission (see below). Second-order Fermi mechanisms, for example in turbulent plasmas, are unlikely to have efficiencies high enough to produce the observed luminosities of γ rays. It is also possible to accelerate particles (specifically, electron-positron pairs) in a dynamo arising from differential rotation of an accretion disk (Lovelace 1976). Once relativistic particles are accelerated, more can be made secondarily in collisions, perhaps in the form of cascades. If highly relativistic neutrons can be made in such collisions very close to the central engine, they can escape freely to decay at a distance $\sim (\gamma/10^5)$ parsecs away, perhaps creating the radio jet if the protons whose collisions created the neutrons were initially moving in a uniform direction (Eichler and Wiita 1978; Giovanoni and Kazanas 1990; Mastichiadis and Protheroe 1990).

In the Milky Way, cosmic-ray protons are about 100 times more numerous than electrons. If the same holds true in blazar jets, the efficiency of γ-ray production through hadronic collisions in the jets could compete with inverse Compton scattering by the electrons (Mannheim 1993). Unfortunately, the protons are otherwise not directly observable, so this idea is difficult to test at present.

REVIEW OF MULTIWAVEBAND OBSERVATIONS

All of the processes discussed in the previous section must be occurring at some level in blazars. The question of which of these mechanisms dominate the γ-ray emission can only be answered observationally. We therefore turn now to a discussion of the observational status of blazars detected at γ-ray energies.

The most useful observations for testing models are those that measure simultaneous multiwaveband spectra at multiple epochs with good time coverage. Unfortunately, such observations were not obtained during the first two years of CGRO's lifetime, since it was not then clear which types of active galaxies might be detected in substantial numbers, nor what strategy one should use to test the theoretical models. What do exist are multiwaveband spectra obtained from data that are not quite simultaneous except at certain well-sampled frequencies.

Four such multiwaveband spectra of γ-ray bright quasars are shown in Fig. 1. In two of the cases, *periods of high γ-ray flux are contemporaneous with enhanced levels of synchrotron emission.* Given the timescales — as short as one month or less — of many high-amplitude synchrotron flares (Robson *et al.* 1993), the sparse time coverage of these observations could easily have caused us to miss millimeter-wave to infrared variations associated with the high γ-ray states. So, two out of four ain't bad. Reich *et al.* (1993) also find that times of high γ-ray flux correspond to times of high millimeter flux.

Multiwaveband spectra of a small number of sources show that the X-ray luminosity is not midway (on a logarithmic scale) between the γ-ray and infrared luminosities (see Fig. 2; the June 1991 spectrum of 3C 279 shows the same effect with nearly simultaneous data; Hartman *et al.*, in preparation). Because of this, the

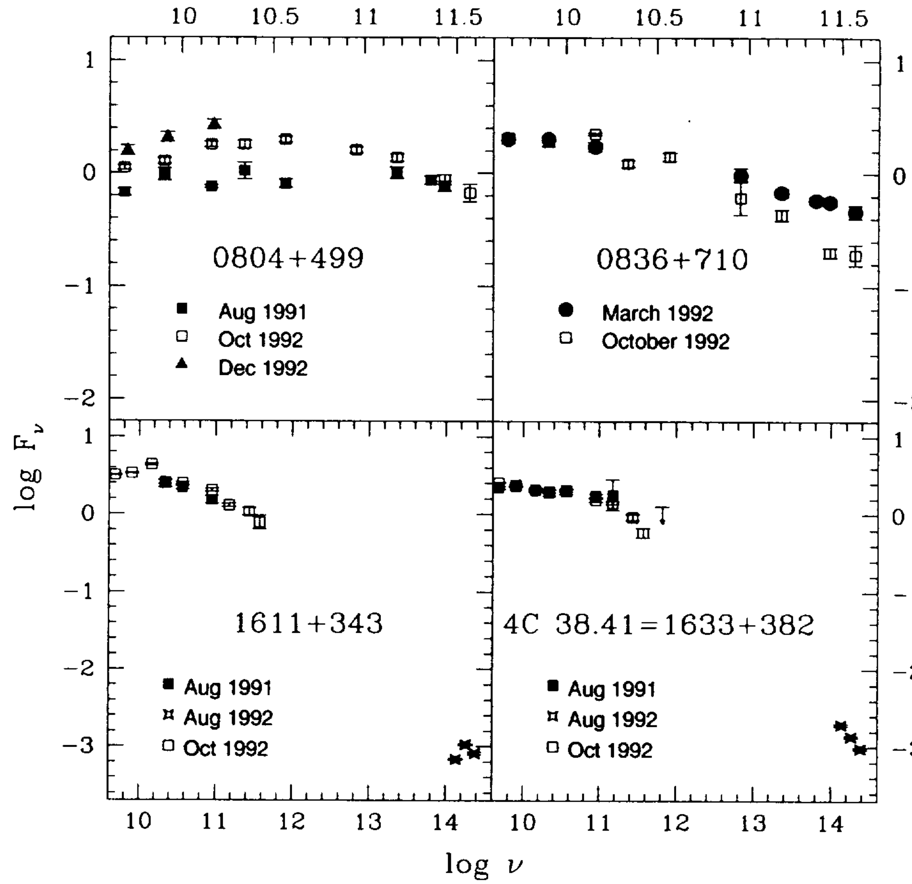

Figure 1. Simultaneous radio to submillimeter spectra of four blazars. Epochs of measured strong γ-ray emission are: 0804+499 and 0836+710 — Jan & Mar 1992; 1611+343 and 4C 38.41 — Sept 1991. Note that the frequency scales are different for the top two panels than for the bottom two. From Bloom *et al.* (1994).

spectra are inconsistent with second-order (but *are* consistent with first-order) SSC emission as the origin of the γ rays (see Bloom and Marscher 1993).

The multiple CGRO observations of PKS 0528+134 provide an opportunity to compare γ-ray and radio emission, since the light curve has been well sampled since mid-1991 at 4.8, 8.0, 14.5, 22, and 37 GHz (Zhang *et al.* 1994). As shown in Fig. 3, γ-ray high states (Hunter *et al.* 1993; Sreekumar *et al.* 1993) occurred near the beginning of a major high-frequency radio flare in mid-1991, which later propagated to lower frequencies as the outburst became progressively less opaque. The very high γ-ray flux of March 1993 preceded the peak of the strongest 37 GHz flux observed thus far by 25 days, whereas the factor of ~ 10 lower γ-ray flux observed in late May 1993 (Nolan *et al.* 1993) was measured during the declining phase of the 37 GHz outburst. The source was opaque at this frequency (the turnover frequency increased from 7 to 60 GHz,

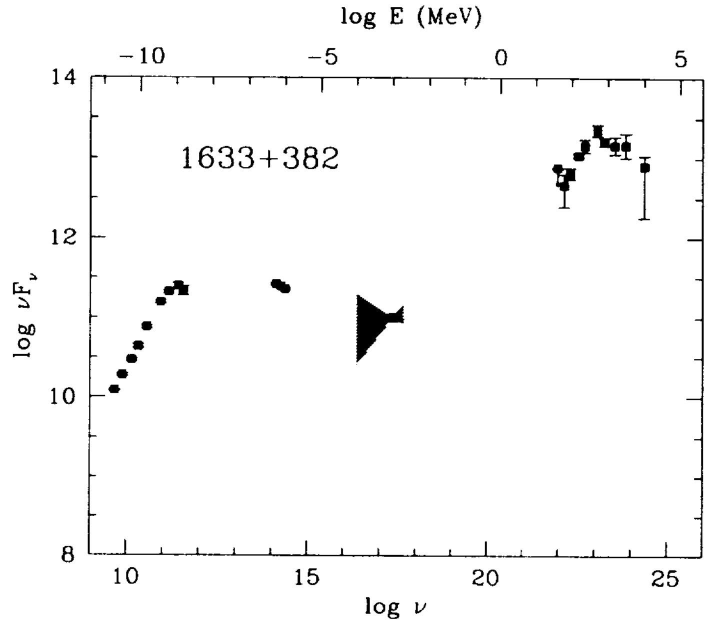

Figure 2. Multi-waveband spectrum of the quasar 1633+382, detected by EGRET in September 1991. Although the X-ray data, obtained in August 1992, are not simultaneous with the γ-ray data, the X-ray flux would have to have increased by about 1.5 orders of magnitude for the γ-ray emission to be explained by second-order inverse Compton scattering.

indicating that the core had become very active after a quiescent period), hence the 37 GHz peak was probably time delayed relative to the optically thin maximum at $\nu \gtrsim 100$ GHz. Nevertheless, these observations show that lags between γ-ray and synchrotron flares can be measured given sufficient time coverage with millimeter, submillimeter, infrared, and optical telescopes during and after (and before, if possible) the CGRO pointings. As discussed in the following section, this is crucial for testing the theoretical models.

It may be that all γ-ray flares are associated with synchrotron outbursts; better time coverage at optically thin frequencies will tell. The converse is not true, however. In the quasar 4C 39.25, the site of the synchrotron flare is a knot in the jet rather than the VLBI core region (Marscher *et al.* 1991; Alberdi *et al.* 1993). Despite a flux density that has risen to over 10 Jy at radio wavelengths, no γ rays were detected by CGRO in September–October 1992 (Fichtel *et al.*, in preparation). We tentatively conclude that the synchrotron outburst must be in the core for there to be a γ-ray flare. The above authors model the radio behavior of 4C 39.25 in terms of a bent relativistic jet, with the fractional time rate of increase of flux density being the same at all observed radio frequencies above 4.8 GHz. Zhang *et al.* (in preparation) find that this extends to the X-ray emission, as predicted by the bent jet model if the X-rays arise from SSC emission: both the X-ray and radio flux densities increased by 30% between April 1991 and April 1993.

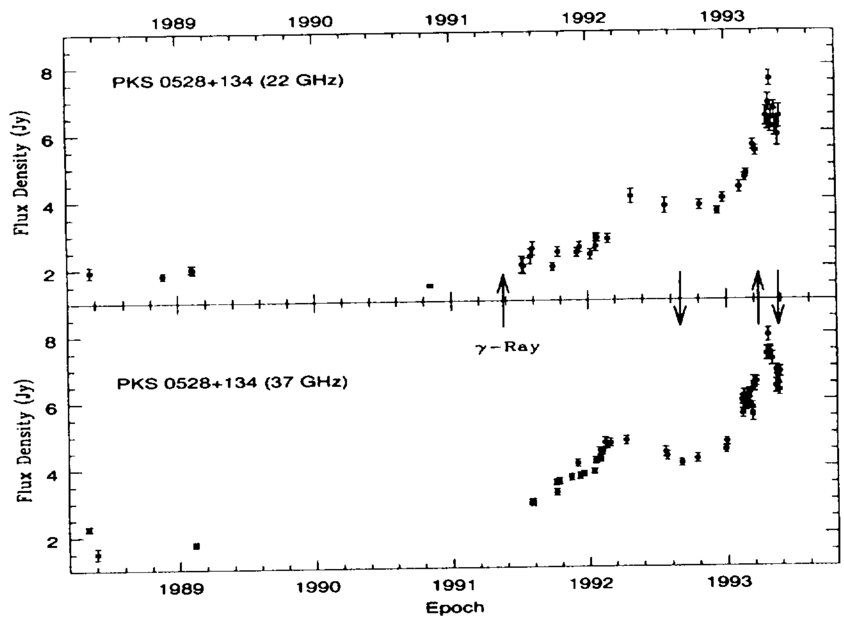

Figure 3. 22 and 37 GHz light curves of PKS 0528+134. Epochs of CGRO γ-ray observations are indicated by the arrows; up-arrows: very strong detections; down arrows: upper limits to flux, $\sim$ 10 times lower than the strongest detection. From Zhang *et al.* (1994).

SUMMARY AND FUTURE PROSPECTS

The best way to establish and study the connections between γ-ray and X-ray emission and lower frequency synchrotron emission is through simultaneous multiwaveband monitoring. According to the standard relativistic jet model (see Marscher 1993 for a discussion), the emission regions at different wavebands are connected but lie at different distances from the central engine. The models for the γ-ray emission mechanism, however, differ in the relative placement of the sites of high-energy and lower frequency emission. Each of the models therefore predicts a particular time lag (which can be zero) from one waveband to the next. One can therefore potentially use multifrequency observations to discriminate among the models. For example, variations occurring in shocked regions near the core of the radio jet should result in simultaneous brightness and polarization fluctuations at higher frequencies and slightly time-delayed and less pronounced variations at lower frequencies (but still above the self-absorption turnover). In models in which relativistic electrons in the jet scatter thermal photons from the accretion disk (Coppi *et al.* 1993; Dermer *et al.* 1992), ultraviolet flares should occur before γ-ray and X-ray flares, which should later lead into radio–infrared outbursts. It is even more likely in the context of this model for the flare to be caused by an enhanced flow of electrons in the stream, in which case a γ-ray and X-ray flare would precede a radio–infrared outburst with no uv flare. In the accelerating jet model of Maraschi et al. (1992), the ultraviolet and γ-ray emission varies simultaneously, as does the infrared and X-ray emission, but the latter fluctuations follow the former by a day or so, with the submillimeter outburst occurring later still. A γ-ray flare arising from the region near the central engine should precede by at least a week any corresponding synchrotron (millimeter-wave to infrared and possibly optical) flare. Blandford (1993) has argued that, if the acceleration of relativistic electrons occurs throughout the jet, the energy dependence of the pair-production process might restrict the higher energy γ rays to arise from greater distances from the central engine. If this occurs, a γ-ray flare should be seen (and die) first at lower energies and later at higher energies. There are a number of other possible combinations, since precisely where the emission regions at each frequency lie depends on the details of the jet geometry and particle acceleration.

There is an even simpler observational test that can discriminate between the two basic inverse Compton scattering models (SSC vs. EICS) if an optically thin synchrotron flare is observed (at millimeter to optical wavelengths). The synchrotron flux density F_ν should vary as $B^{1+\alpha}N_0V$, where B is the magnetic field strength, N_0 is the normalization of the electron energy distribution, V is the volume, and α is the spectral index ($F_\nu^{\rm S} \propto \nu^{-\alpha}\delta^{3+\alpha}$). The SSC flux density varies as $F_\nu^{\rm SSC} \propto N_0 F_\nu^{\rm S}$, such that the response of the γ-ray flux to an increase in the number of relativistic electrons should be greater than that of the synchrotron flux. This is not true for the EICS model, for which variations in the number of electrons causes the scattered flux to vary as $N_0 V\delta^{3+\alpha}$, which is at most the same as the amplitude of the corresponding synchrotron flare unless the magnetic field varies in the opposite sense as the number of electrons, which seems unlikely. Therefore, by comparing the relative amplitudes of γ-ray vs. millimeter to optical flares, a choice can be made between the SSC and EICS models (see also Maraschi and Ghisellini, these proceedings, who have independently developed this argument).

In general, past programs have not had sufficient time coverage to fulfill the promise of the technique of using multiwaveband observations to discriminate among the various proposed models for γ-ray emission, the acceleration of particles, and the structure of the innermost regions of blazar jets. Still, much has been learned. More intensive monitoring is planned during the next few years, which should result in major advances in our knowledge of the physics of blazars and how they produce such high luminosities in γ rays.

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